The CONUS Coherent Reactor Neutrino Scattering Experiment

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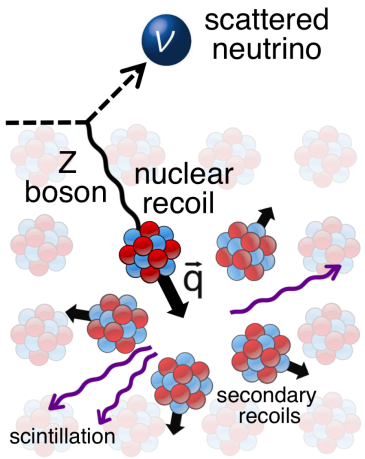
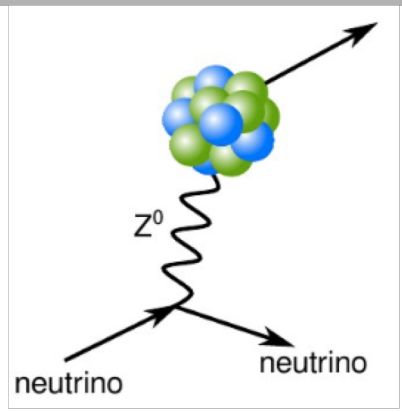


WORKSHOP
THE MAGNIFICENT CEVNS
NOVEMBER 2-3, 2018 CHICAGO, IL USA

Coherent Neutrino Scattering

Z-exchange of a neutrino with nucleus
➔ nucleus recoils as a whole



$$Q_w = N - (1 - 4\sin^2\theta_w)Z$$ **~ N**

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$ **~ N^2**

N ~ 40 ➔ N^2 = 1600 ➔ detector mass 10t ➔ few kg

Important: Coherence length ~ 1/E
→ need neutrinos below O(50) MeV for typical nuclei
→ low energy E_ν ←→ lower cross sections ←→ maximal flux!

- **Conceptual very interesting - see e.g.**
  E. Akhmedov, G. Arcadi, ML, S. Vogl, JHEP 1810 (2018) 045, arXiv:1806.10962
- **Form factors $F(q^2)$: How precise? ➔ low versus higher q^2**

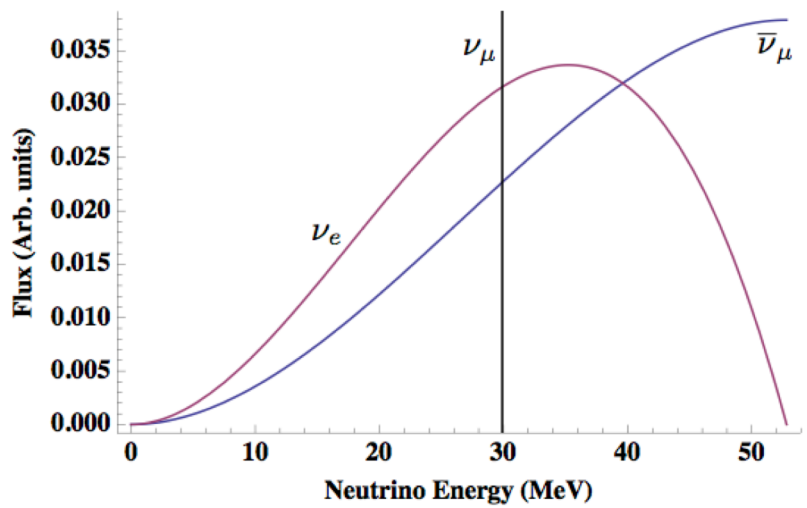
Two Paths

Low energy ν's from accelerators:

- π-decay-at-rest (DAR) ν source
- different flavors produced
- relatively high recoil energies

➔ close to de-coherence

➔ **1st observation of CEνNS by COHERENT in 2017**

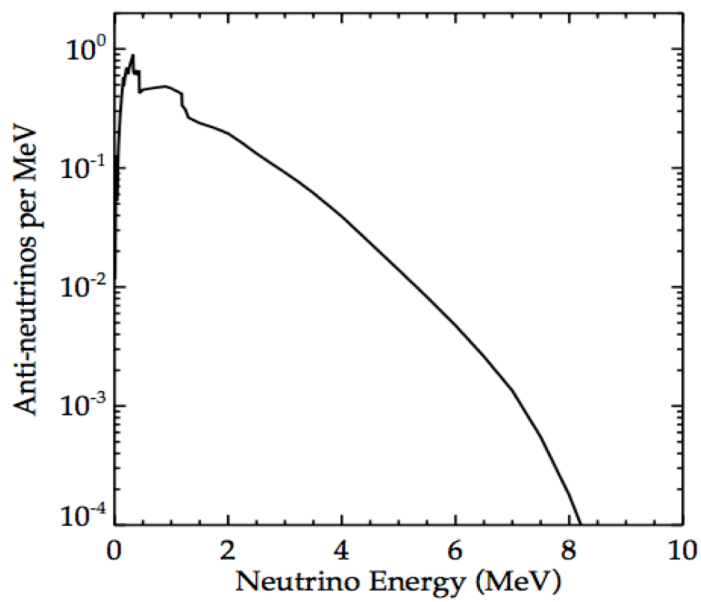


Anderson et al., 1201.3805

Reactors:

- lower ν energies than accelerators
- lower cross section – higher flux
- different flavor content implications for probes of new physics

➔ **CONUS**



Vogel et al. 1981, Kopeikin 2012

Experimental Requirements

- measure nuclear recoil energy T

  for E_ν = 10 MeV ➔ $T_{max} \simeq$ 3 keV (in Ge)

- energy loss due to quenching (Lindhard)

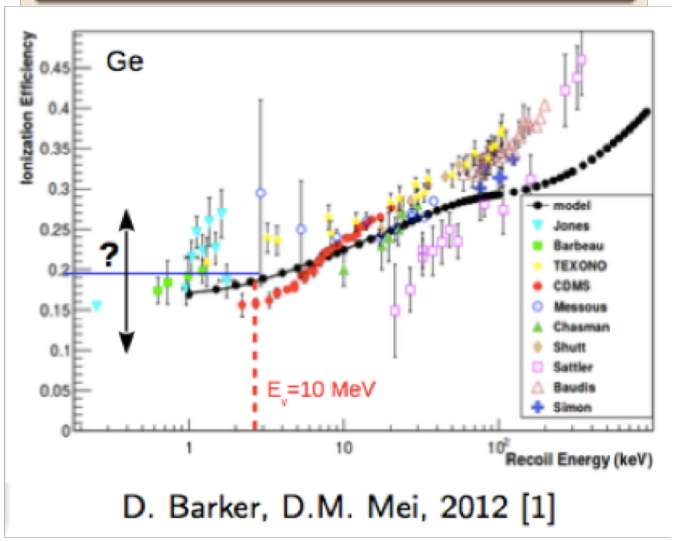
  ➔ Quenching Factor (QF)

  QF down to 0.2 in Ge → 600 eV

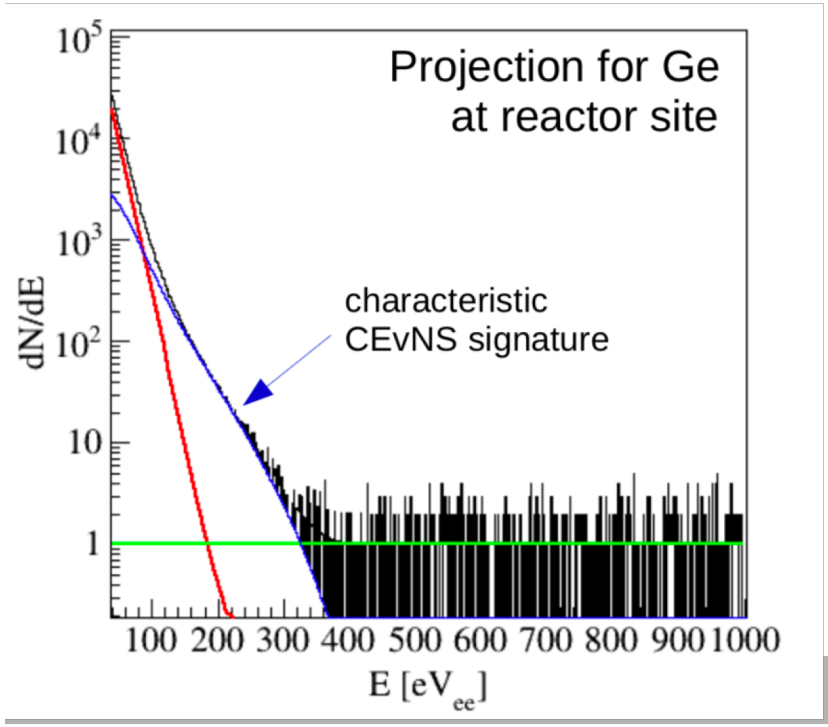
  ➔ include systematic uncertainty

  ➔ QF improvements (EX, TH) & old data

$$T_{max} \approx \frac{2E_\nu^2}{m_n(N+Z)}$$



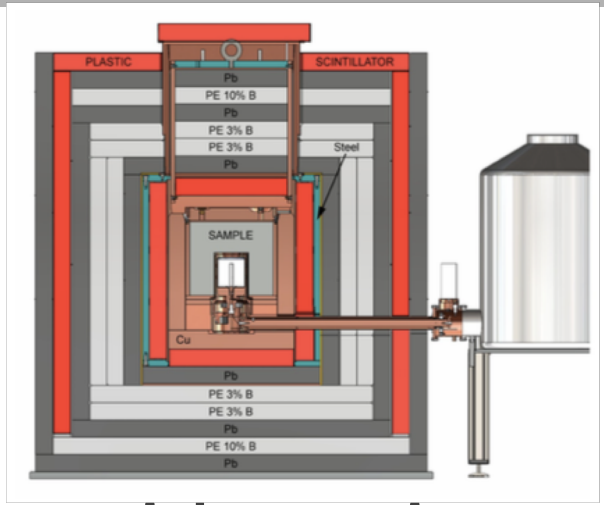
D. Barker, D.M. Mei, 2012 [1]



detection of CEνNS signal:

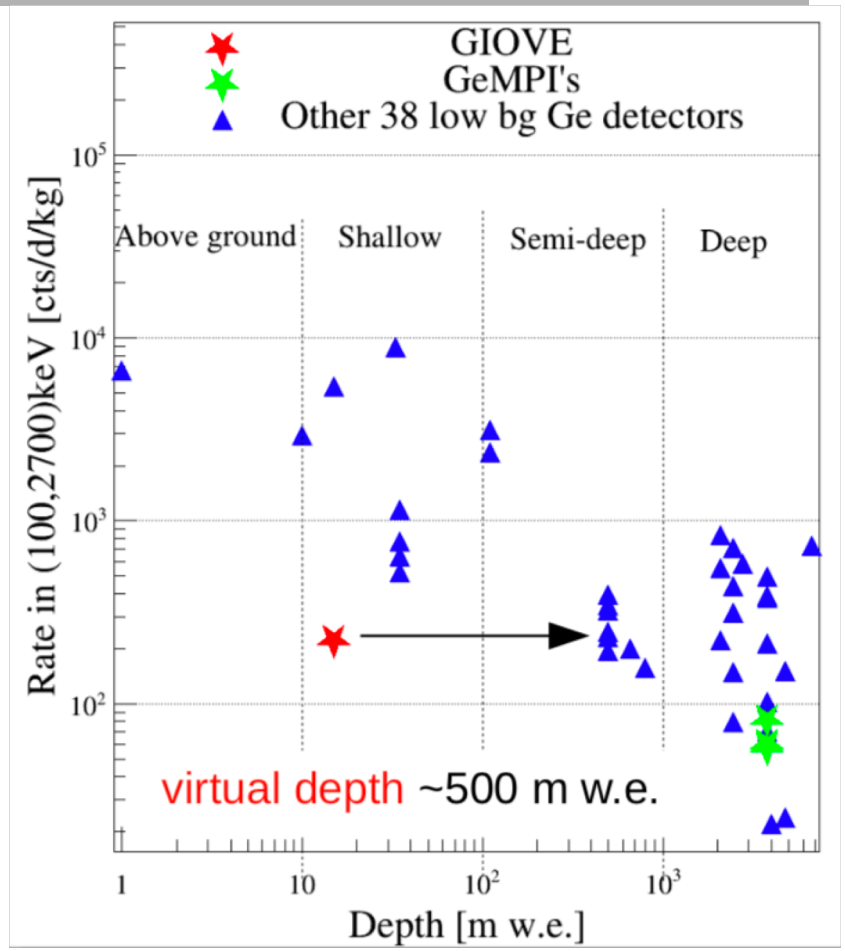
- highest ν flux
- low noise threshold (sub keV) + mass
- very low background
  - radio-pure materials
  - "virtual depth" shielding

``Virtual Depth'': The GIOVE Shield



- R&D at MPIK
- main purpose: material screening @ shallow depth (15 mwe)
- coaxial HPGe detector (m_{act} = 1.8 kg)
- radio-pure passive shielding
  - Pb, B-doped PE, μ-veto, OFHC Cu
- active veto: optimized to reduce μ's and μ-induced signals
  - plastic scintillators with PMTs
  - 99% muon veto efficiency (dead time ~2%)

(^{226}Ra: 70μBq/kg, ^{228}Ra: 110μBq/kg, ^{228}Th 50μBq/kg)

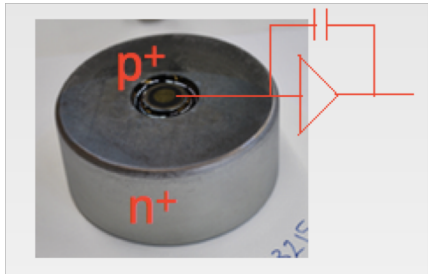


``virtual depth'' ➔ UG projects close to surface

G.Heusser et al.,Eur.Phys.J. C(2015)75:531

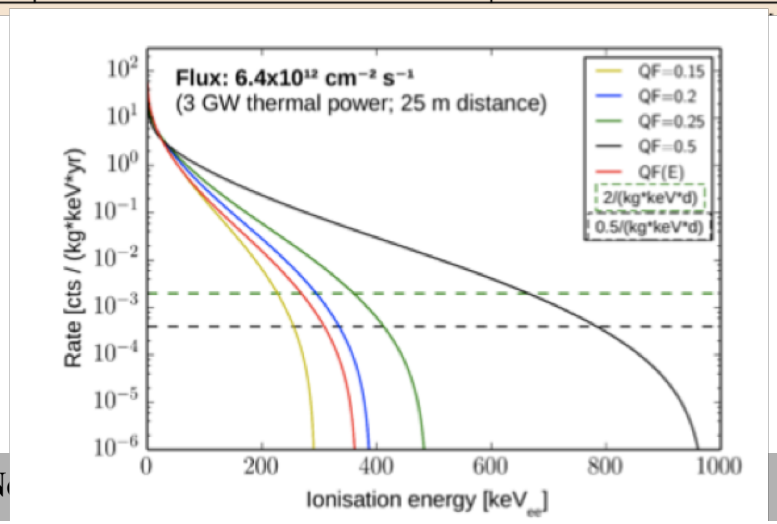
Event Rates for a conceivable Experiment

1kg detector: BEGE or SAGE type germanium diode
Distance D=15 m; 3.9GW ←→ flux = $3.12*10^{13}/cm^2/s$
Background ~ 1/kg/keV/day



S[1/yr] / B[1/ye] / R=S/B

Pulser/Threshold [eV]	QF = 0.15	QF = best fit	QF = 0.25
60 / 180	971 / 61 / 15.8	2 173 / 85 / 25.6	9 194 / 127 / 72.3
65 / 195	588 / 58 / 10.1	1 488 / 81 / 18.4	6 962 / 123 / 56.4
70 / 210	352 / 55 / 6.4	1 014 / 78 / 13.0	5 272 / 120 / 44/0
75 / 225	207 / 52 / 4.0	686 / 75 / 9.2	3 989 / 117 / 34.2
80 / 240	120 / 49 / 2.5	460 / 71 / 6.5	3 012 / 113 / 26.7
85 / 255	69 / 46 / 1.5	306 / 68 / 4.5	2 269/110/20.7



➔ Not trivial, but doable on a short time scale!

➔ Even a 1kg detector can detect CEνNS

➔ Upscaling…

Maneschg, Rink, Salathe, ML

The CONUS Experiment

Combine:

- highest neutrino flux ➔ close to power reactor
- lowest detection threshold ➔ R&D
- best background supression ➔ "virtual depth"

➔ COherent NeUtrino Scattering experiment

C. Buck, J. Hakenmüller, G. Heusser, M. Lindner, W. Maneschg, T. Rink, T. Schierhuber, H. Strecker - Max Planck Institut für Kernphysik (MPIK), Heidelberg

K. Fülber, R. Wink - Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf

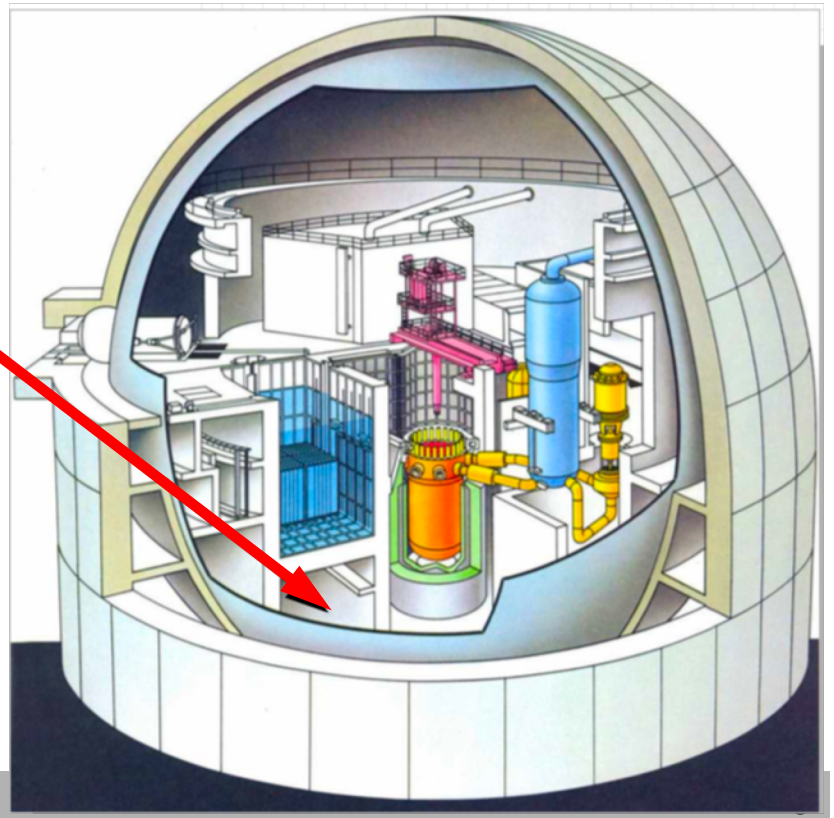
The CONUS Reactor Site

The Brokdorf (Germany) nuclear power plant:

thermal power 3.9 GW_{th}
detector @ d=17m
➔ ν flux: 2.4 x $10^{13}/cm^2/s$
very high duty cycle

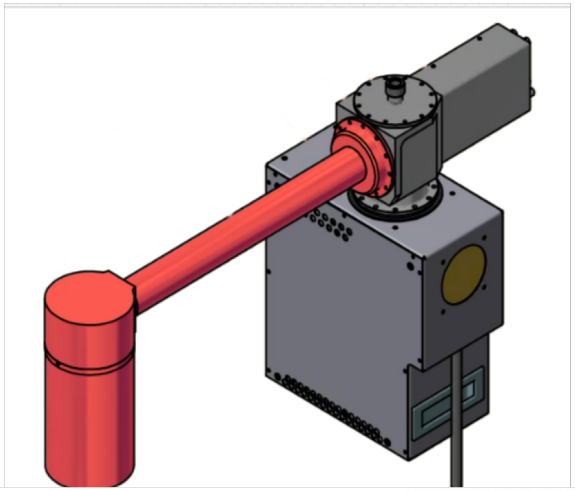
➔ very intense integral neutrino flux
E_ν up to ~ 8 MeV → fully coherent

- **overburden 10-45 m.w.e**
- **access during reactor operation**
- **measurements of n background**
- **ON/OFF periods**
  ➔ backgd. only measurement



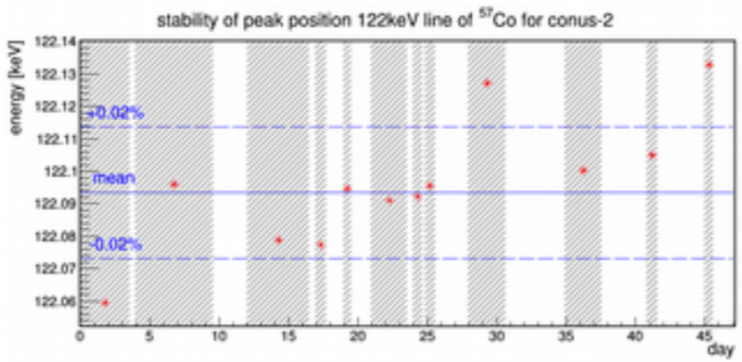
Detectors: CONUS 1-4

- p-type point contact HPGe
- 4x 1kg – **active mass 3.85kg**
- Spec. for pulser res. (FWHM) ≤ 85eV
  → noise threshold ≤ 300eV
- electrical PT-cryocoolers
- ultra low background components
- close collaboration with Canberra

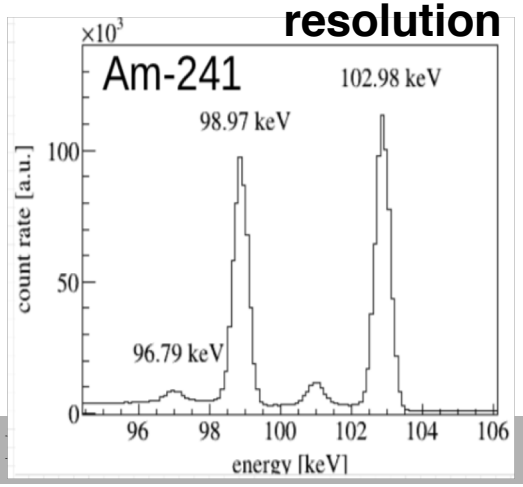


Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

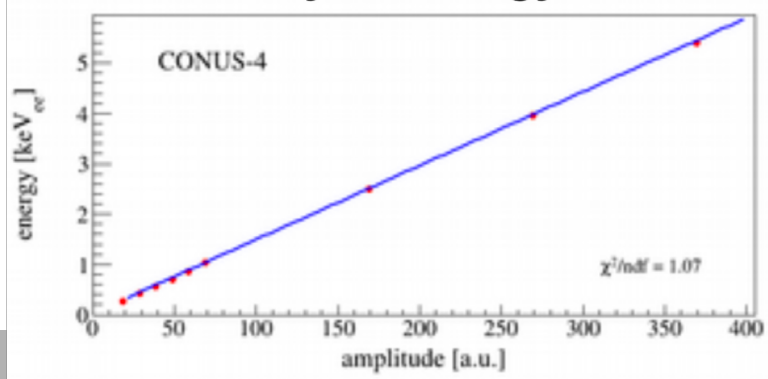
Long term stability
Under lab. Conditions:
stan. dev. of peak position:
+-15eV (+-0.02%)
(within 45 days)

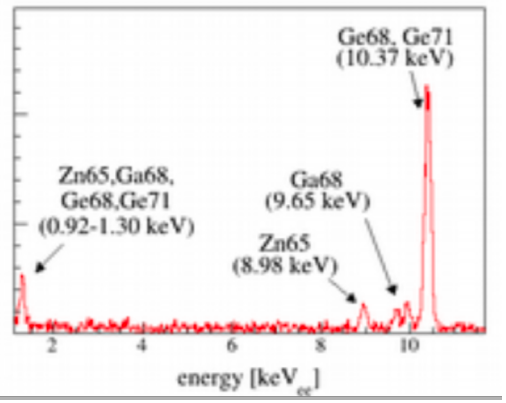


resolution



Linearity of energy scale

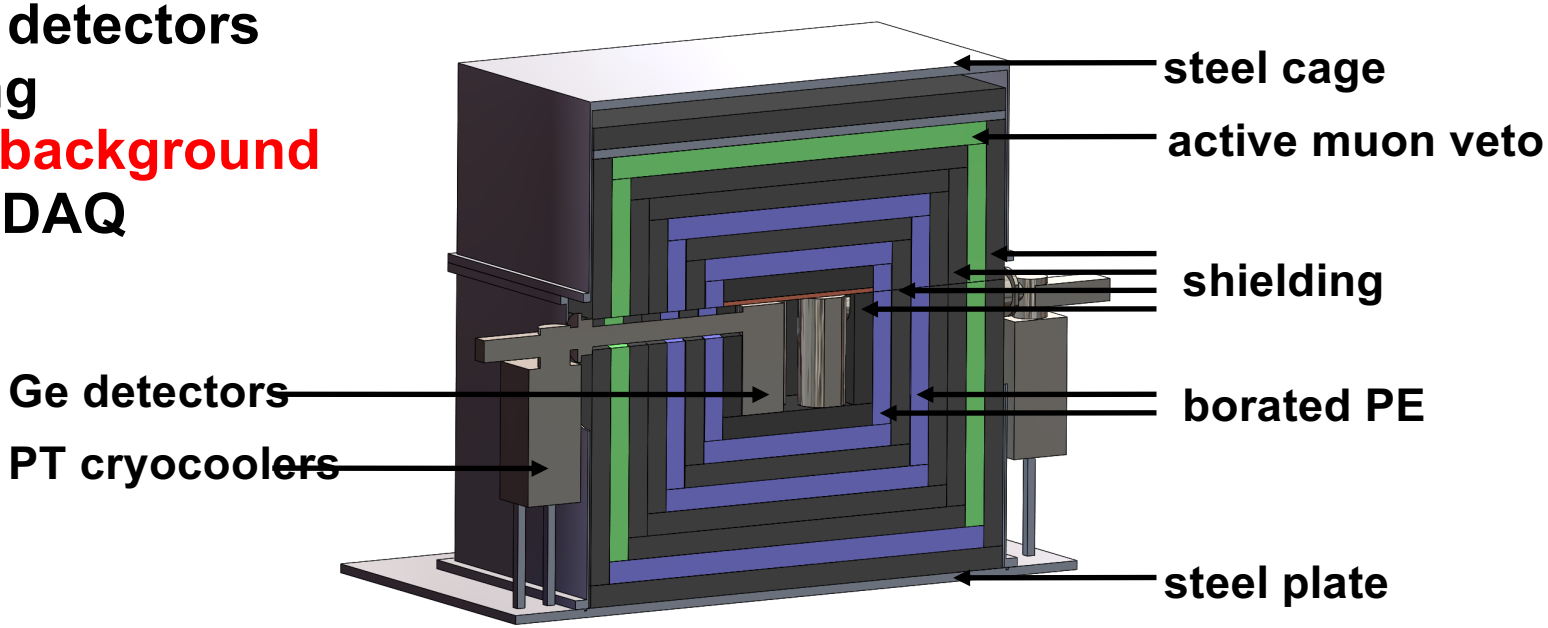




The CONUS Detector

Components: ← about 1.2 m →

- ``virtual depth" shielding
- 4 Germanium detectors
- PT cryocooling
- → all ultra low background
- electronics & DAQ



Successful combination of three essential improvements:

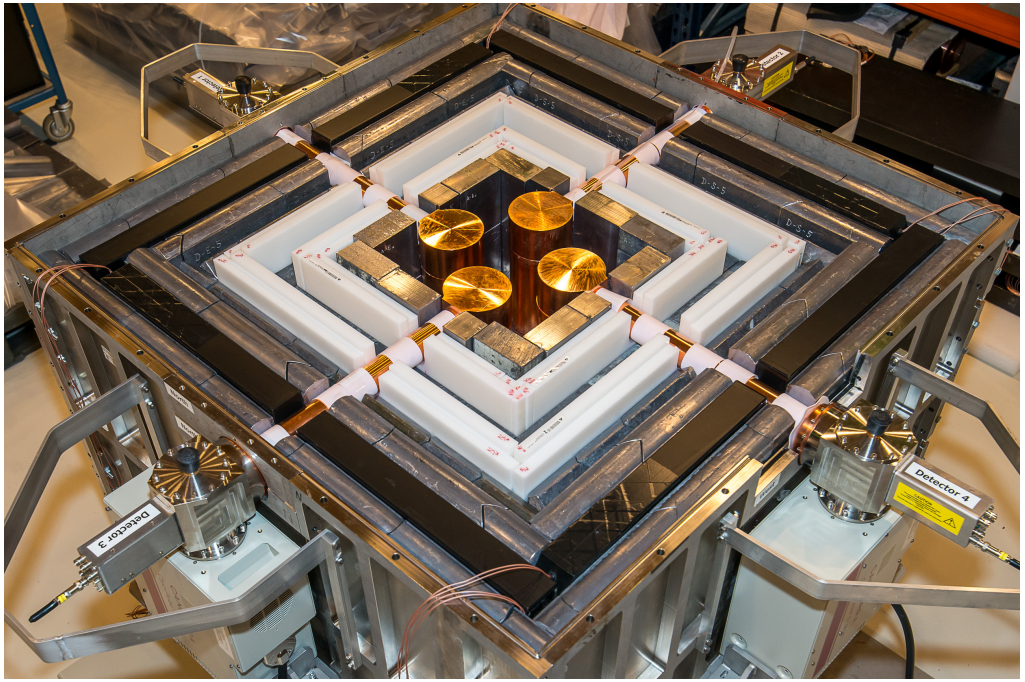
- excellent shielding (GIOVE @ MPIK = "virtual depth")
  - new detectors with very low thresholds & PT cryocooling
  - site with highest neutrino flux

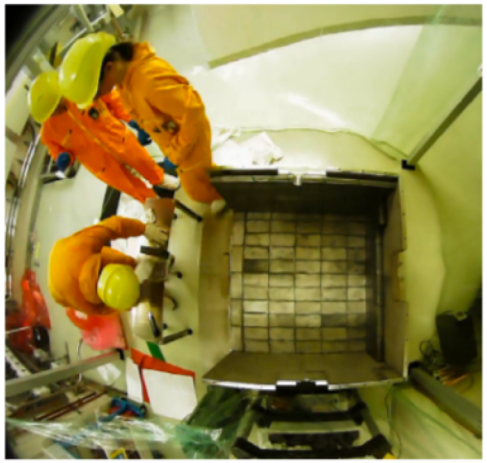
Start of the project summer 2016 → data taking sping 2018

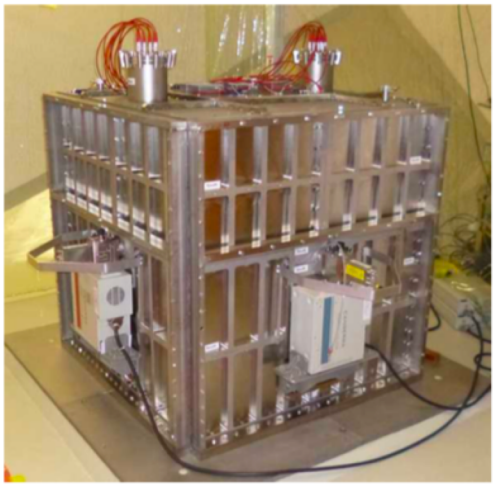
Test Assembly and Installation @ Reactor

assembly at MPIK UG lab
→ characterization
→ commissioning

installation @ Brokdorf
→ full assembly
→ commissioning







Neutron Spectroscoy @ Reactor Site

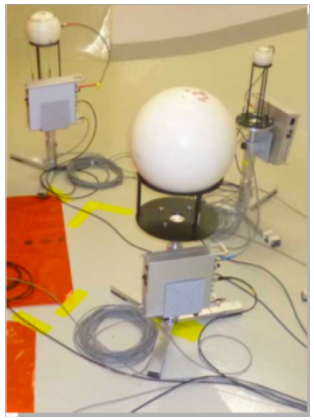
Ge recoils from fast neutrons can mimic CEνNS

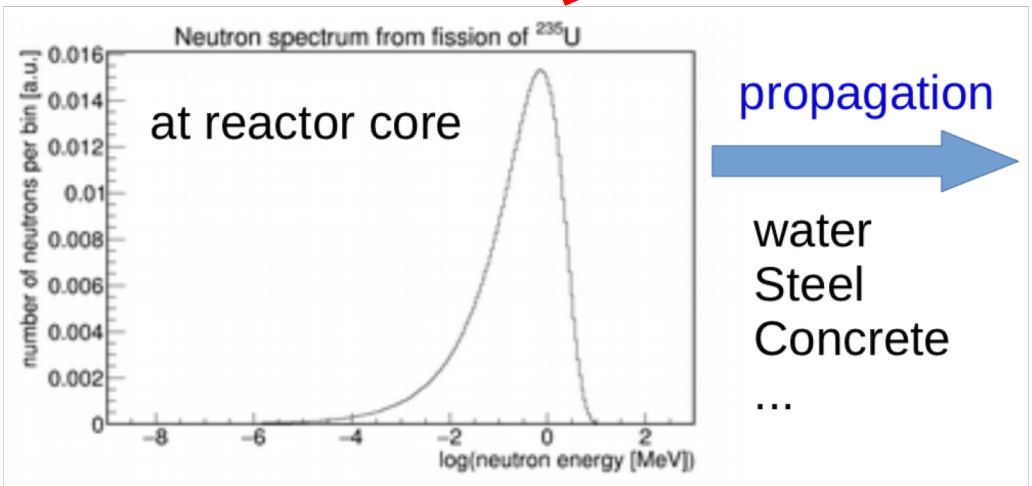
Fast neutron classes	Corr. with therm. power
μ-ind. in Pb inside shield	No
μ-ind. above ceiling	No
(α,n)-reactions from walls	No
fission n from spent fuel rods	No
fission n from reactor core	Yes

outside of shield

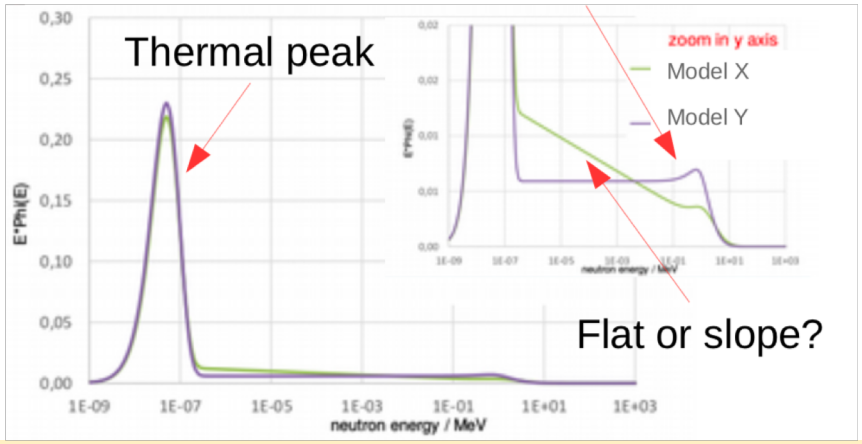
→ **NEMUS**

setup by PTB
→ on-site neutron spectroscopy





Remaining fast neutrons?



1. Neutron field highly thermalized (>80%), correlated with thermal power

→ fully absorbed by B-PE layers (MC)

2. Residual fluence: if at all – epithermal from reactor - cosmic 100 MeV n: negligible

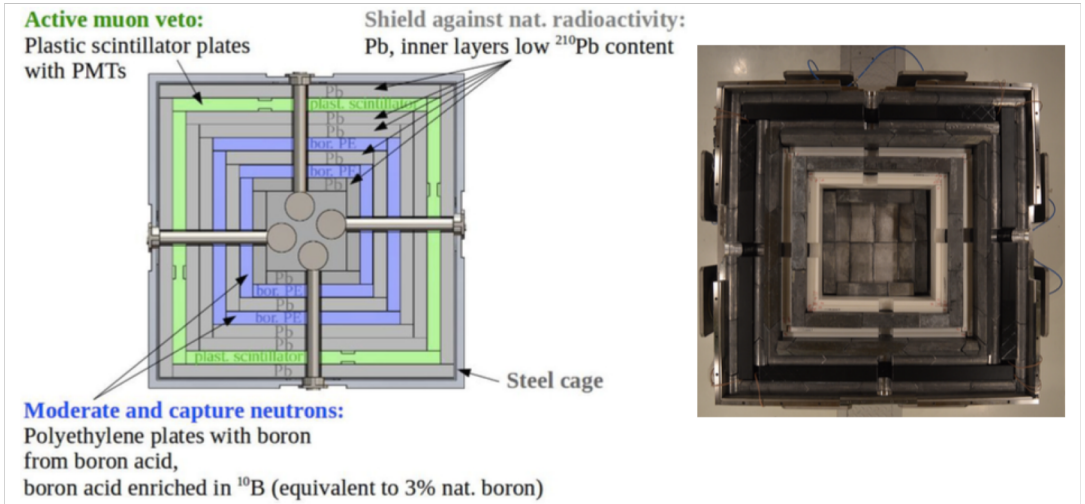
→ reactor-correlated fast n inside shield ≃ negligible **→ detailed publication soon**

Background Reduction

Site:

- MPIK UG lab (15 m.w.e.): reduction ~10^3 , low activity concrete
- Brokdorf (eff. 24 m.w.e.) → additional backgrounds

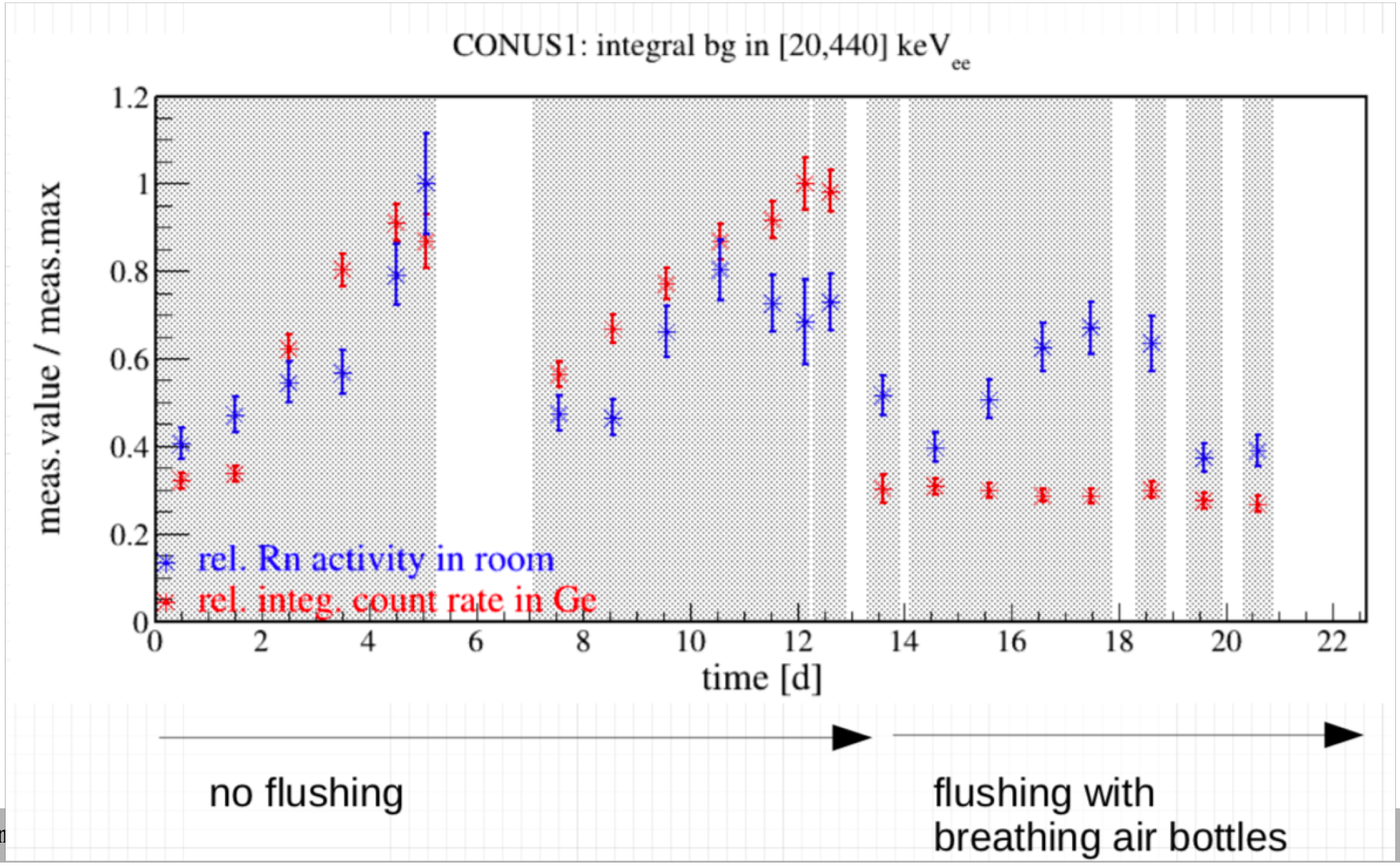
Shield:



- optimized layers
- innermost layer Pb: Bremsstrahlung ~Z^2, self-shielding ~Z^5
- ^{210}Pb → lead from Freiburg Minster: <2Bq/kg
- layers of borated PE
- validation: μ-flux @ MPIK-UG → propagate (Geant4 based MaGe)
- Bonner sphere measurements (with PTB)
- use information from CONUS and GIOVE

Radon Mitigation @ Reactor Site

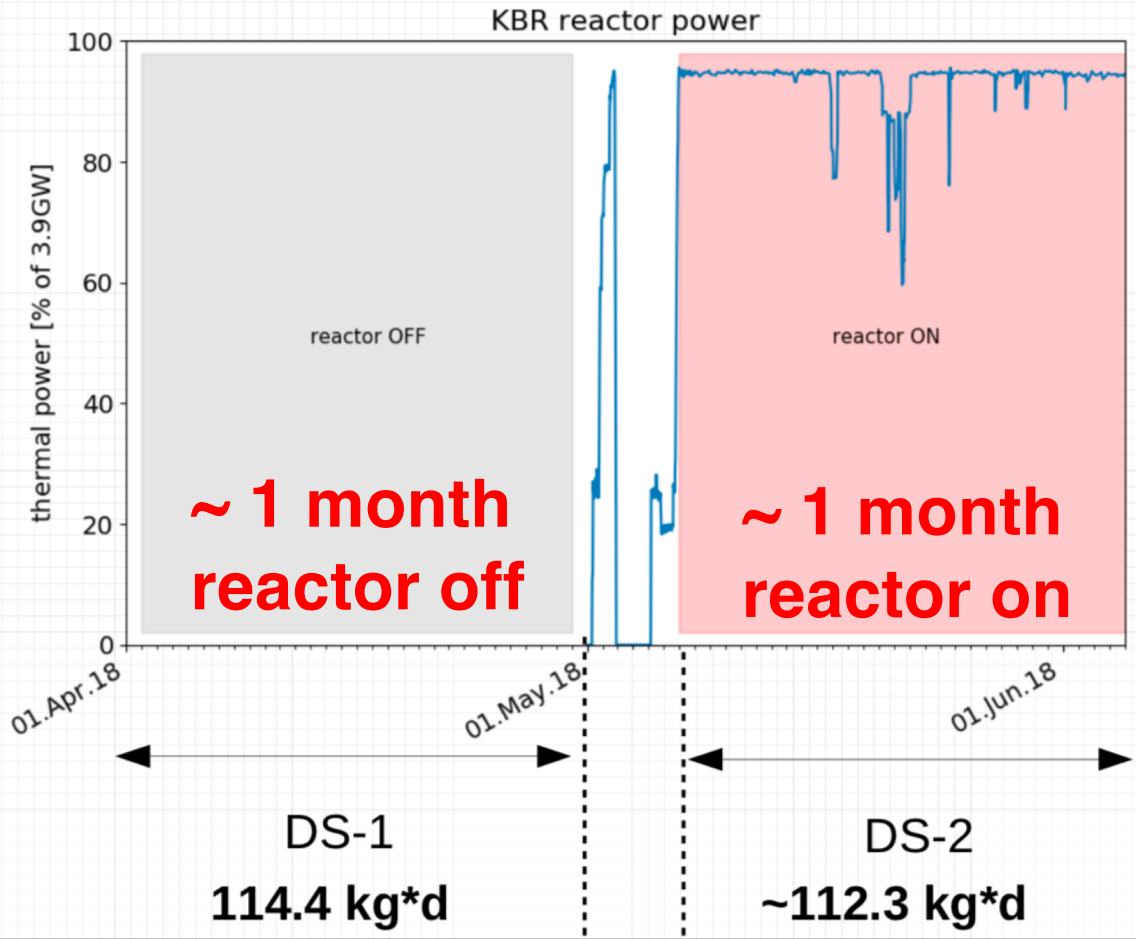
radon at reactor site: closed room, thick concrete walls ➔ 100-300 Bq/m^3
half-life of ^{222}Rn: 3.8d
➔ counter measure: hermetical sealing + flush with breating air bottles ~1 l/min



Data Taking

Begin of data collection: April 1, 2018

Reactor thermal power:



Datasets and exposure:

Detailed analysis of detector stability, backgrounds, ... ➔ no time...

First quick Rate-Only Analysis

➔ **Talk by W. Maneschg @ NEUTRINO 2018**

Define cuts from reactor OFF:

- energy scale calibartion
- quality cuts (noise, suprious evt. red.)
- conservative ROI, trigger eff. ~80% (for each detector)
- not yet included: bg red. due to slightly reduced x-ray bg contribution in ROI → 'slow pulses'

Efficiencies:

- active volume (96 ± 2)%
- muon AC % ind. tr. Eff. (97.9 ± 0.1)%
- threshold trigger efficiency (per detector)

Data release June 2018	counts	counts/d/kg (*)
Reactor OFF (114 kg*d)	582	--
Reactor ON (112 kg*d)	653	--
ON-OFF (exposure corr.)	84	0.94
Significance	2.4 σ (stat.)	2.3 σ

➔ **observe excess which matches expected CEνNS range**

Meanwhile

More data: 1 month → ca. 6 months
Improved understanding of detectors and backgrounds
MC simulations
➔ important improvements

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More data: 1 month → ca. 6 months
Improved understanding of detectors and backgrounds
MC simulations
→ important improvements

→ **Results will be published soon...**

The Future: CONUS100

Upscaling to 100kg ➔ very interesting potential
high statistics ➔ precision ➔ various interesting topics…

assume:
100kg detector
4GW @ 15m
flux ~$3*10^{13}/cm^2/s$
background 1/kg/day

BSMsens=ΔS/S

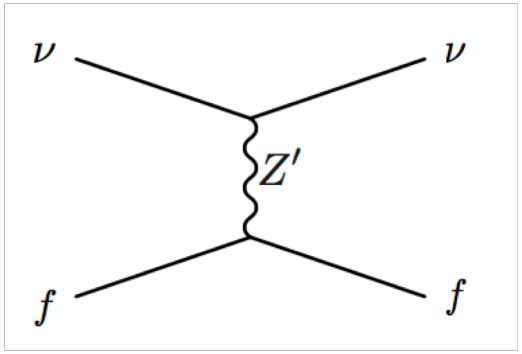
Puler/Thresh [eV]	QF=0.15	**BSMsens**	QF=BF	**BSMsens**	QF=0.25	**BSMsens**
40 / 120	647 474/ 8291 / 78.1	$1*10^{-3}$	965 999/ 10 775/89.7	$1*10^{-3}$	$2.9*10^{6}$/ 15 158 / 189	$6*10^{-4}$
45 / 135	407 092/ 8 036 / 50.7	$2*10^{-3}$	664 316/ 10 519/63.2	$1*10^{-3}$	$2.1*10^{6}$/ 14 866 / 144	$7*10^{-4}$
50 / 150	254 745/ 7780 / 32.7	$2*10^{-3}$	458 072/ 1 0264/44.6	$1*10^{-3}$	$1.6*10^{6}$/ 14 574 / 84.9	$8*10^{-4}$
55 / 165	158 109/ 7 524 / 21.0	$3*10^{-3}$	315 843/ 9 971/31.7	$2*10^{-3}$	$1.2*10^{6}$/ 14 318 / 84.9	$9*10^{-4}$
60 / 180	97 066/ 7 305 / 13.3	$3*10^{-3}$	217 277/ 9 716/22.4	$2*10^{-3}$	919 435/ 13 026 / 65.6	$1*10^{-3}$
65 / 195	58 827/ 7 049 / 8.3	$4*10^{-3}$	148 848/ 9 460/15.7	$3*10^{-3}$	696 196/ 13 770 / 50.6	$1*10^{-3}$
70 / 210	35 154/ 6 830 / 5.1	$5*10^{-3}$	101 386/ 9 204/11.0	$3*10^{-3}$	527 204/ 13 514 / 39.0	$1*10^{-3}$
75 / 225	20 711/ 6 575 / 3.2	$7*10^{-3}$	68 573/ 8 949/7.7	$4*10^{-3}$	398 867/ 13 222 / 30.2	$2*10^{-3}$
80 / 240	12 042/ 6 355 / 1.9	$9*10^{-3}$	46 008/ 8 730/5.27	$5*10^{-3}$	301 231/ 12 966 / 23.2	$2*10^{-3}$
85 / 255	6 924/ 6 136 / 1.1	$1*10^{-2}$	30 598/ 8 474/3.6	$6*10^{-3}$	226 910/ 12 711 / 17.9	$2*10^{-3}$

BSMsens=ΔS/S S[1/yr] / B[1/yr] / R=S/B

Maneschg, Rink, Salathe, ML

Searches for new Physics: NSI's

NSI's ←→ new physics at high scales
Which are integrated out
Z', new scalars, … ➔ ε_{ij}



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\ \gamma^\rho\ \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\}$$

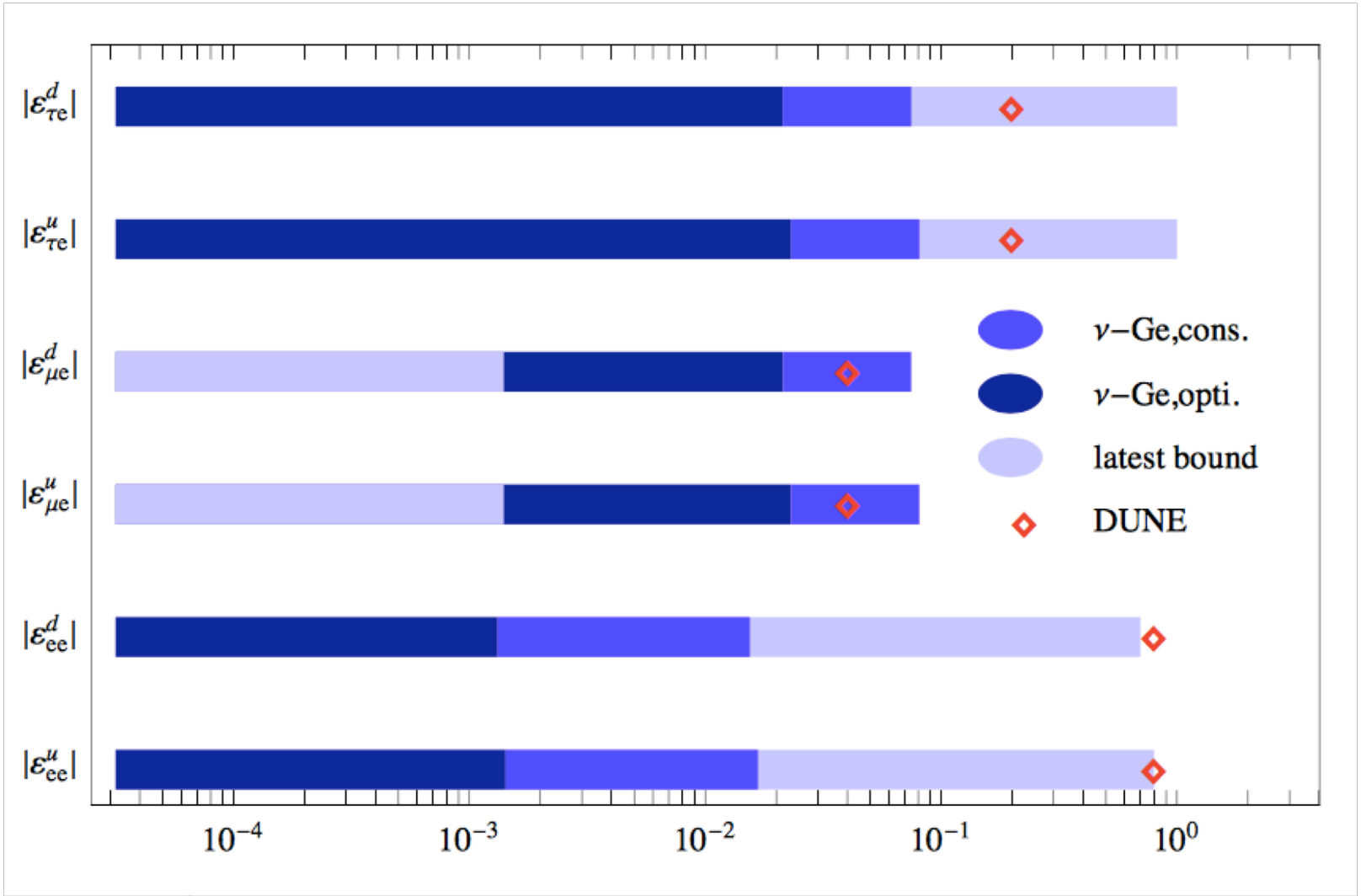
Barranco et al. 2005

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

➔ Competitive method to test TeV scales
$\varepsilon = 0.01$ ←→ TeV scales

NSI-Potential

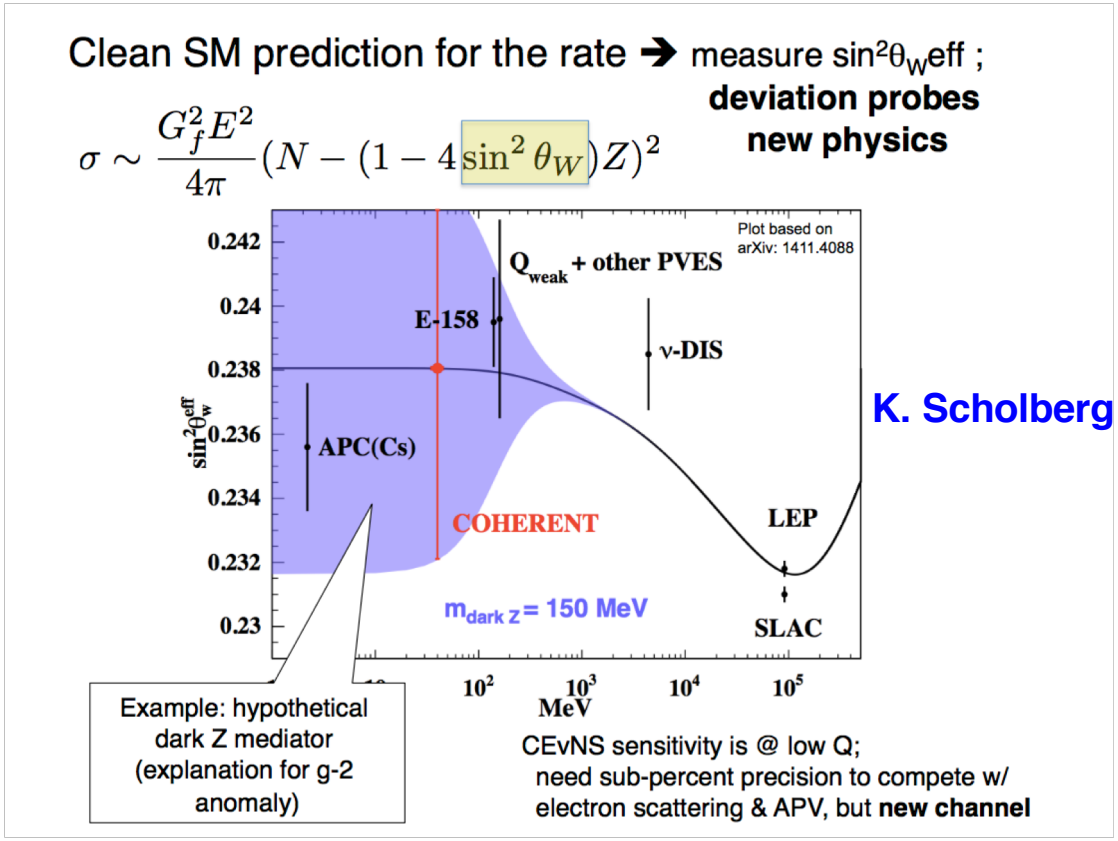
100kg detector, 5 years operation @ 4GW **ML, W. Rodejohann, X.Xu**



~10 TeV **~TeV**

Precise Measurement of $\sin^2\theta_W$ at low E

BSM sensitivity ←→ precision
10^{-3} → $\Delta\sin^2\theta_W = 0.006$
10^{-4} → $\Delta\sin^2\theta_W = 0.0006$



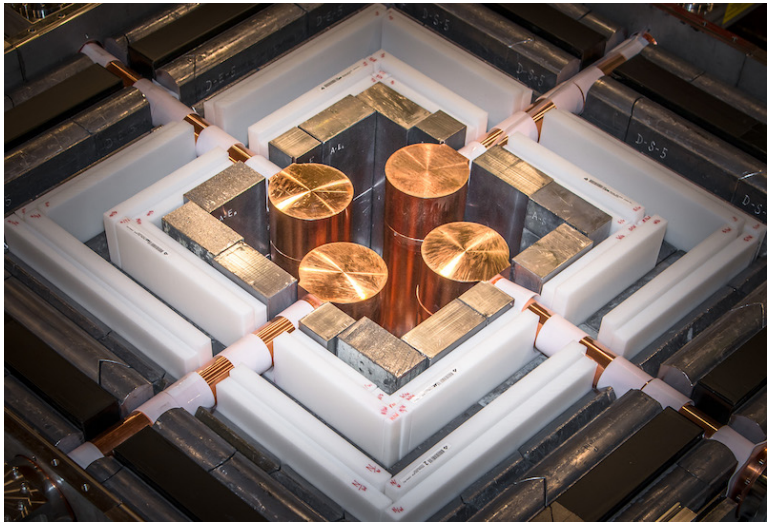
K. Scholberg

Other topics:

- explore coherent scattering ←→ by itself interesting, direct DM experiments
- sterile neutrino searches (if still alive...)
- nuclear form factors in neutrino light
- nuclear safe-guarding
- ...

Conclusions

- Neutron measurement at reactor site:
  → highly thermalized field is well shielded
- **Successful background suppression**
  by active and passive shield,
  background modelling ongoing
- Very detailed information on anti neutrino source = reactor available



- First data release in June 2018:
  114 kg*d / 112 kg*d of reactor OFF/ON data
  → observed an excess in the ROI with statistical significance of 2.4 σ
  → First hint for CEvNS observation at a nuclear reactor
- Ongoing data taking (1→5M) & refined analysis **→ publication soon!**
- **Very good and interesting potential for O(100kg) size detector:**
  mag. moments, NSI's, $\sin^2\theta_W$, sterile ν's, $F_i(q^2)$, decoherence,spectrum, monitoring